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CURRENT PROBLEMS OF THERMAL SOUNDING OF THE ATMOSPHERE FROM ARTIFICIAL EARTH SATELLITES

L.A. Pakhomov and Yu.M. Timofeyev

ABSTRACT: This paper discusses current problems of thermal sounding of the atmosphere from artificial satellites on the basis of measurements of the outgoing radiation from the Earth-atmosphere system in the CO_2 absorption band with its center at 15 microns. This limitation of the contents is associated with the fact that the first stage in the practical realization of methods of indirect sounding as an operative method of obtaining raw data on a global scale will clearly be based on precisely this method of measurement. However, the paper also deals with several general aspects of indirect sounding which touch on the physical bases of long-range methods of measuring the distributions of atmospheric parameters from artificial Earth satellites. The article is concluded by a list of references that reflect the results obtained by Soviet investigators in the period from 1969 to 1972 and which constitute the basis of the present work. /2*

1. Successful experiments in the establishment of vertical temperature, moisture and ozone profiles, performed by American and Soviet artificial Earth satellites, have completely confirmed the suggested feasibility of indirect satellite methods. As was demonstrated in a number of theoretical papers as far back as the late 1950's, the characteristics of the field of outgoing radiation from the Earth-atmosphere system include information on the physical state of the atmosphere. These indirect methods constitute one of the principal means of obtaining global data on the vertical temperature, moisture and ozone profiles which are required for the solution of problems in the numerical forcasting of the weather. /3

The most important data which can be obtained by means of satellite measurements, both from the standpoint of their use in forecasting and from the

*Numbers in the margin indicate pagination in the foreign text.

standpoint of the accuracy of the characteristics obtained, are the vertical temperature profiles. However, in the statements of the inverse problems it is advantageous to use a complex approach in which a problem is formulated from the very beginning with respect to the complex of basic physical parameters of the atmosphere: temperature, moisture and ozone. This is governed by a number of reasons, the most important of which are the following:

1. Usually, the functions of the outgoing thermal radiation, measured aboard satellites, do not depend on a single atmospheric parameter but on a complex of parameters.

2. The parameters of the physical state of the atmosphere are intercorrelated. The utilization of information concerning intercorrelation, taken into account in a complex approach, in many instances leads to a significant increase in the accuracy of representation of characteristics (for example, moisture and ozone).

3. The complex approach makes it possible to avoid unnecessary and costly obstacles to the accuracy of the measurements, inasmuch as it takes into account both the measurement errors themselves and the errors that are caused by fluctuations in the atmospheric parameters.

4. Finally, regardless of the fact that the principal parameter which can be determined with high accuracy is temperature, the data on other atmospheric characteristics, even if obtained with moderate accuracy, in many instances are of great value.

At the present time, the inverse problems have been formulated and /4 partially experimentally solved for various portions of the spectrum of the outgoing radiation. Thus, for example, the problem of analysis of the temperature patterns may be solved by interpretation of measurements in the CO_2 bands at 4.3 microns and 15 microns, in the oxygen band in the microwave region of the spectrum. Different regions of the spectrum have different advantages and shortcomings of both a physical and instrumental nature: different sensitivity to temperature variations, penetrating ability during propagation in clouds, measurement accuracy, etc. It seems logical to expect that the optimum arrangement for indirect sounding would consist of apparatus for various spectral regions. In this connection, it is necessary to conduct theoretical and especially experimental studies of problems of complext utilization of measurements in various regions of the spectrum.

The value of the information on the parameters of the physical state of the atmosphere, obtained by means of an artificial Earth satellite, depend to a significant degree on the following characteristics: accuracy of resolution, universality, the altitude range of resolution and spatial resolution. We can expect that the requirements with regard to these characteristics will differ for different scientific and applied purposes. Let us consider the possibility of indirect methods of satisfying the requirements that arise in problems of numerical weather forecasting. Before characterizing the possible accuracy of indirect temperature resolution, let us dwell on some other properties of satellite data.

The altitude range of resolution of the temperature profile is governed by the spectral resolution, the spectral range and the methods of sounding under cloud conditions. From the standpoint of spectral resolution, there are no great difficulties at the present time in determining the temperature up to altitudes of 30-40 km, and up to 60-80 km by using special devices for the infrared region and soundings in the microwave region. In the presence of cloud cover in the field of vision of the instrument, the acquisition of data on the temperature of strata below the clouds is complicated. As possible methods of solving this problem, attention is currently being given to methods of sounding using instruments with high spatial resolution, as well as the application of statistics. Particular attention is being paid to the use of /5
measurements in the microwave region, the radiation in which has a high penetrating ability.

The spatial resolution required in problems of numerical weather forecasting is achieved by means of modern instruments. In many instances, the measurement data have a much higher resolution, as, for example, in the IR sounding under conditions of partial cloud cover. The required spatial resolution may be obtained by appropriate averaging.

II.. Let us proceed now to discuss the basic characteristics of the resolution of temperature accuracy. The accuracy of determination of a temperature profile on the basis of spectral measurements is dependent in a complex fashion on a number of factors.

1. The spectral range.

2. The spectral resolution.

3. The measurement accuracy of spectral brightnesses, characterizing the random and systematic error.

4. The optimality of the measurement conditions of the spectrum.

5. Adequacy of the determination of the optical properties of the atmosphere.

6. The mathematical algorithm used in the analysis.

7. State of the atmosphere during measurement of the spectrum.

Let us examine the above factors in detail.

Thus, at the present time the final selection of the optimum region or combination of regions of the spectrum has not been accomplished with respect to the problem of thermal sounding. As we mentioned earlier, it is advantageous at the present time to discuss the problem as a complex of factors. Nevertheless, on the basis of the available practical results from thermal sounding from artificial Earth satellites, we can state that the best operative system will be based on IR sounding in the 15 micron band of CO_2.

One of the principal problems is the determination and selection of an optimum arrangement of the spectral intervals and their widths. This process is most important when the spectral measurements are conducted with a multi-channel radiometer in which the number, position and width of the spectral intervals are fixed. These problems are of less importance when instruments are used that have continuous measurement of the spectrum, such as interferometers and the like.

The problem of the selection and allocation of the spectral intervals at at a given spectral resolution in the 15 micron band was discussed by Twomey in a simplified form. /6

V.P. Kozlov has suggested an algorithm and has obtained some interesting results in connection with the optimization of the measurement conditions in this same band using the statistical method. This problem was studied in a work by Westwater and Strand for the microwave region.

Further development of the problem of optimization of measurements was accomplished in the papers by O.M. Pokrovskiy. He suggested a universal method which would make it possible to solve the problem of the optimal conditions of measurement with various *a priori* assumptions regarding the desired solution: limitation, smoothness, applicablity to an empirical set.

For a quantitative estimate of the information, the desired temperature profile contained in the measurements with a given accuracy of spectral intensities, the method mentioned utilizes the classical measurement of information according Shannon. Numerical realization of the method consists in the successive calculation of the increases in information, on the basis of which the selection of the optimal spectral intervals.is made. As the input data for the problem, the value of the dispersion of the measurement errors is employed (level 1.5-2%), as well as the transmission function of the real atmosphere, obtained by the direct method. The results of the calculations have made it possible to draw a number of very important practical conclusions that touch on the development of an optimum measurement:

1. At the measurement accuracy given above, independent information regarding the solution of the inverse problem (the temperature profile) may be obtained from measurements in six spectral ranges.

2. The centers of these optimal intervals in many instances coincide with the centers of the intervals of the multichannel radiometers of the U.S.A. However, it has been found that high spectral resolution, utilized on all channels, is unnecessary, because it can amount to 10-20 cm^{-1} for relatively transparent channels.

At the present time, the most complete study has involved the influence of random errors in measurement of the spectrum on errors in establishing the temperature profile. As a rule, the source of stationary random error is the intrinsic noise of the radiation receiver and the preamplifier. Experience /7 shows that for purposes of remote thermal sounding it possible to have a mean square relative error in measurement on the order of 0.5-1%. Achievement of such measurement accuracy is a difficult problem in itself, especially since it necessary to ensure certain dynamic characteristics of the instruments.

Increasing the information content of the method of indirect thermal sounding in global system of observations is associated primarily with overcoming the influence of the cloud cover. To do this, one of the effective solutions is increasing the spatial resolution of the instrument, inasmuch as 60-70% of the observations involve conditions of partial cloud cover. If we consider the fact that the distorting effect of cloud cover has its greatest effect on measurements in relatively "transparent" channels, the importance of information concerning the possibility of utilization of a mean spectral resolution in these channels becomes obvious (10-20 cm^{-1}).

In addition to the random errors, systematic errors are of definite significance in the formation of resolution errors, and the principal source of them consists of the errors in absolute calibration of the instrument. Experience has shown that at the present time, problems of absolute calibration have acquired primary importance, inasmuch as the volume of spectral observations by means of different kinds of spectral instruments is growing steadily. For a correct comparison of the results that are obtained, checking and refinement of optical properties of the atmosphere, it is necessary to have data which have been obtained by means of instruments that were calibrated according to a single radiation standard.

Current concepts regarding the accuracy of thermal sounding were obtained essentially through comparison of reduced data from the results of radio sounding. These comparisons have shown that the mean-square deviations of the reduced and Rawinsond profiles (at the current measurement accuracy and with knowledge of the optical characteristics of the atmosphere) amount to

1.5-3.0°C. In view of the lack of correctness of similar comparisons (the difference in the physical principles of measurement, different spatial coverage, space-time divergence of the measurements, etc.), we can say that the values listed for the deviations give only an approximate idea of the accuracy of the analytical process. If we consider that the indirect method /8 provides some average temperatures of the layers of the atmosphere (the averaging ability requires further radiation), it is natural to assume a great degree of agreement between the average temperatures of rather extensive layers. A confirmation of this is provided by the results of comparison of geopotential profiles.

These difficulties in determining the accuracy of analysis of temperature indicate that conclusions and findings regarding accuracy of indirect thermal sounding may be made only with respect to certain problems of utilization of these data.

III. Even at the current accuracy of measurements, an important role in the determination of high-quality data regarding the temperature of the atmosphere is played by the accuracy of determination of the optical properties of the real atmosphere.

The most precise methods of obtaining the characteristics of absorption of carbon dioxide are the calculation methods that are based on the utilization of data on the parameters of the fine structure of the absorption spectra. At the present time, such data are available and extensive calculations have been made of the transmission functions for various bands and atmospheric situations. A certain degree of empiricism is employed in calculating absorption in the wings of the CO_2 bands, as well as in the calculation of the influence of the absorption by water vapor. This makes it necessary to have a correction of the transmission functions in the process of solution of the inverse problem or the development of special experiments for refining the characteristics of absorption of the real atmosphere. For a complete and qualitative solution of the problem, it is necessary to have further laboratory and natural measurements of the transparency of the atmosphere, theoretical work in the area of the fine structure of the absorption bands, in comparison of the experimental

data on transmission with theoretical data, etc. Similar studies will help significantly in increasing our knowledge of the properties of the absorption of the real atmosphere and improving the accuracy of their analysis. It is necessary to emphasize in this context that improvement of the quality of the instruments, for example, the accuracy of the measurements, without appropriate improvements in the optical properties of the atmosphere will not lead to a /9
noticeable increase in the accuracy of the analysis.

Significant improvements on the level of improving the model of the absorption of the atmosphere and the study of variations in absorption are required for a corrective consideration of the possible influence of aerosol and dimers of water vapor.

As numerous experiments performed on computers have shown, the utilization of any method of solution of the inverse problem is characterized by the dependence of the accuracy of the analysis on the accuracy of the statement of new kernel of the equation. This understandable, because in the first approximation the errors in the statement of the kernel are equivalent to the errors in the measurement of the radiation spectrum.

Numerous sources of error in the statement of the kernel of the equation may be broken down into two classes which have different physical natures. The first category consists of those errors which are associated with inaccuracies of the methods of obtaining the transmission functions of the atmosphere and with approximate consideration of the real apparatus function of the measuring device.

These errors are caused by a number of factors:

1. Errors in laboratory measurement of transmission.

2. Errors in approximate methods of the theory of radiation transmission in the atmosphere.

3. Errors in knowledge of the fine structure of the absorption spectra (in the case of the direct calculation method).

4. Inaccuracy of the spectral connection of the measurements and knowledge of the real apparatus function of the instrument.

The second class of errors is caused by deviation of the characteristics of the real atmosphere at the time of the measurements from that model of the distribution of atmospheric parameters for which the kernel of the equation has been calculated. In the first place, this influence of instability of atmospheric temperature, possible variation in the CO_2 content, absorption of water vapor, ozone and possibly the influence of aerosol and dimers of water vapor.

Between the errors in the statement of the kernel of the first and second class there is a theoretical difference. It is a fact that errors of the first class will occur even in the case of an absolutely precise knowledge of the parameters which characterize the state of the atmosphere at the moment of measurement of the spectrum. It is clear that as a function of the accomplishment of the experimental and theoretical investigations, improvement of the calculation methodology, more precise determination of the apparatus characteristics, the errors of the first type will decrease. However, the /10
errors of the second kind clearly will always be present in real representations of the temperature profile if satisfactory methods of correction of the kernel of the equation are not developed.

For correction of the kernel, it is necessary to have the original information from independent measurements, which give for example an estimate of the real content of H_2O vapor, the O_3 concentration, etc. It must be mentioned in this context that the successful utilization of the method of correction depends to a significant extent on how much the errors of the first kind are minimized.

The current picture of the situation with absorption characteristics of the atmosphere in the 15 micron region of the CO_2 band consists in the following:

1. Data are available on the parameters of the fine structure of the 15 micron band of CO_2, which make it possible on the basis of the direct method of calculation to obtain transmission functions with an accuracy of 2-3% on the average (the maximum errors may reach high values). Such

accuracy in the first approximation may be assumed satisfactory. Empirical approaches, consisting in the analytical approximation of the data from laboratory measurements of transmission, are incapable at the present time of providing information with equal accuracy. However, the corresponding expressions in the solution of the inverse problem may be utilized.

2. A semiempirical method has been worked for calculating the influence of water vapor, which makes it possible with sufficient accuracy to take into account its influence in the problem of thermal sounding of the atmosphere.

3. Satisfactory data for this problem do exist in connection with the absorption of O_3 and H_2O.

Hence, at the present time, conditions exist for sufficient minimization of the errors of the first type. Therefore, considerable importance with respect to the accomplishment of indirect thermal sounding is attached to the problem of taking into account the state of the atmosphere at the time of measurement of the spectrum. We have already pointed out that the existence of cloud cover considerably increase the error in analysis. The same result can be produced by excessive presence in the atmosphere of pollution components and aerosols, a change in the content of carbon dioxide, etc.

In addition to the error in the statement of the kernel of the equation, /11 which has to do with the influence of the factors ennumerated above, equal importance in the practical realization of the method of thermal sounding from satellites is attached to the accuracy with which the radiation of the subjacent surface and clouds is taken into account. Errors that are permissible in the calculation of this radiation are equivalent in every way to the errors in the measurement of the spectral brightnesses of the radiation. The principal sources of error are the following factors: inaccuracy of knowledge of effective radiating power of clouds and subjacent surfaces and other characteristics of the interaction of radiation with the clouds.

In conjunction with the above, a number of problems must be solved:

1. It is necessary to obtain sufficiently reliable and detailed information regarding the current standards of optical properties of the real

atmosphere and their variation in space and time. Particularly great importance is placed upon a check of the optical state of the atmosphere in carrying out special experiments in comparison with direct and indirect methods of sounding.

2. It is necessary to develop methods of taking into account the variations in the optical properties of the atmosphere and determining the combinations of additional measurements (especially simultaneous satellite observations) which make it possible to utilize these methods in operational practice in sounding.

One of the factors which influences the accuracy of analysis of the temperature profile is the mathematical algorithm that is used in the solution of the inverse problem.

As of the present time, a number of methods of interpretation of the problem of thermal sounding have been proposed. These methods utilize various *a priori* assumptions regarding the desired function.(temperature profile) and are based on various principles of stabilization of the operator of the problem, etc.

A number of authors have made successful use in the interpretation of /12
real measurements of the spectrum of various statistical methods of conversion. It should be mentioned in this context that the "statistics" of the distribution of temperature influence to a large extent the results of the analyses and therefore must be adequate and sufficiently detailed with respect to time and space.

Much attention must be paid to the development of methods of conversion that do not require empirical statistics concerning the desired temperature profile. It is natural that the utilization of these methods is most effective in indirect sounding in those areas of the globe that have a sparse network of radiosounding.

Let us mention some of the problems of mathematical performance of thermal sounding that require solution:

1. Development of methods of improvement of existing methods that will allow determination of the temperature profile with sufficient accuracy over the entire altitude range, i.e., solution of the problem of analysis in the layer near the subjacent surface, in the region of the tropopause, etc.

CONCLUSIONS

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1. The current state of the method of thermal sounding using artificial Earth satellites and radiation in the 15 micron band is characterized by the following:

- there exists a sufficiently well-developed theory of the method of indirect thermal sounding;

- absolute and highly accurate measurements have been carried out on the spectra of the outgoing radiation by means of diverse instruments carried aboard satellites;

- the possibility of analyzing temperature profiles on a global scale has been confirmed experimentally;

- the characteristics of the optimum spectral device have been theoretically established and experimentally confirmed.

2. Further development of the method of thermal sounding as an operative means of obtaining raw data for numerical weather forecasting are associated with the solution of a number of problems:

- refinement of the optical characteristics of the atmosphere and their relationship to the space-time variations of the parameters of atmospheric air;

- development of methods of analyzing the temperature profile in the surface layer and in the region of the tropopause;

- development of methods of correcting the kernel of the equation and determining the body of additional information that is required for this;

- optimization of systems for obtaining additional information and its utilization in the operative system for analysis of the temperature profiles;

- correct comparison of a reduced profile temperature with real distributions. Necessary prerequisites for the solution of this problem are: first, calibration of all of the measuring apparatus according to a single absolute standard; second, time-space matching of the measurements of the spectrum from the artificial Earth satellite with direct temperature soundings of the atmosphere by means of precise Rawinsonds, meteorological rockets and aircraft, accompanied by a number of measurements and observations of other atmospheric characteristics (concentrations of water vapor and gas components, aerosols, etc.).

2. Development of methods of analysis which are maximally suited to specific systems for numerical weather forecasting. /14

3. Selection of optimal methods of conversion in the sense not only of accuracy of analysis but also minimum loss of machine time, minimum *a priori* and other auxiliary information.

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